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Abstract

Most of the finite element programs for design of timber trusses with punched metal fasteners are based on models using beam and fictitious elements. Different models have been used for different types of joints. Common problems for all the models are how to calculate the forces in the nail groups and the plates and furthermore, how big the deformations in the joints are.

By developing an advanced model that includes all parts of the joint, i.e. plate, nail groups and contact it is possible to give a better description of the joint. An advanced model with these properties is presented. The advanced model is capable of calculating sectional forces of more complex joints and the forces in the nail groups and plate are given directly.

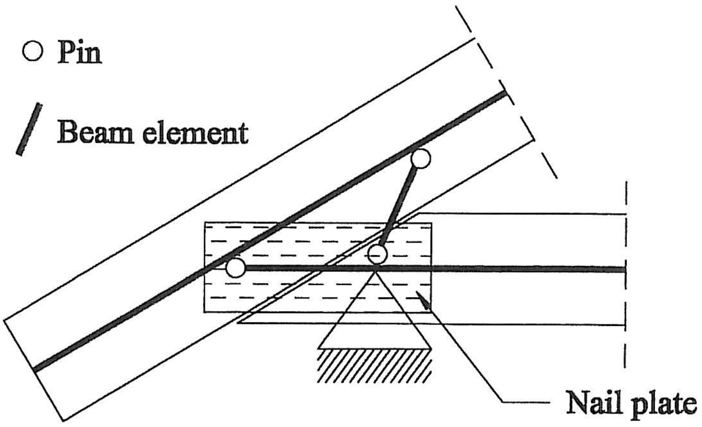
1. Introduction

When designing trusses with finite element programs based on models with fictitious elements it is difficult to determine the forces in the nail groups and plates. An example of a heel joint with a fictitious element is shown in figure 1. The models with fictitious elements cannot predict the deformations of the plate and the stiffness of the joint is not changed as a function of the size and location of the nail plate. This makes it difficult to predict the stiffness and strength capacity for new types of joints.

With the models used today a splice joint in e.g. the top chord of a truss can only be considered as a fully rigid joint or as a pinned joint even though the joint in reality will react like something in between.

Considering all the above-mentioned problems it seems reasonable to develop an advanced model that takes some of the missing parts into account. In Foschi (1977) theories were given to develop separate nail, plate and contact elements.

Figure 1: Heel joint with fictitious element.



With a model that includes these elements it is possible to estimate the forces in the elements directly, the deformations in the joints are given and the model can take into account if there is a gab between the timber members.

The model has been further developed and calibrated with a few joint types in Nielsen (1996). The model is implemented in TRUSSLAB, a program package in the MATLAB environment.

In August 1998 a Ph.D. project for further analysis and development of this subject was started at Aalborg University, Denmark. The state of the art of the model is described in this paper.

2. Description of the Advanced Model

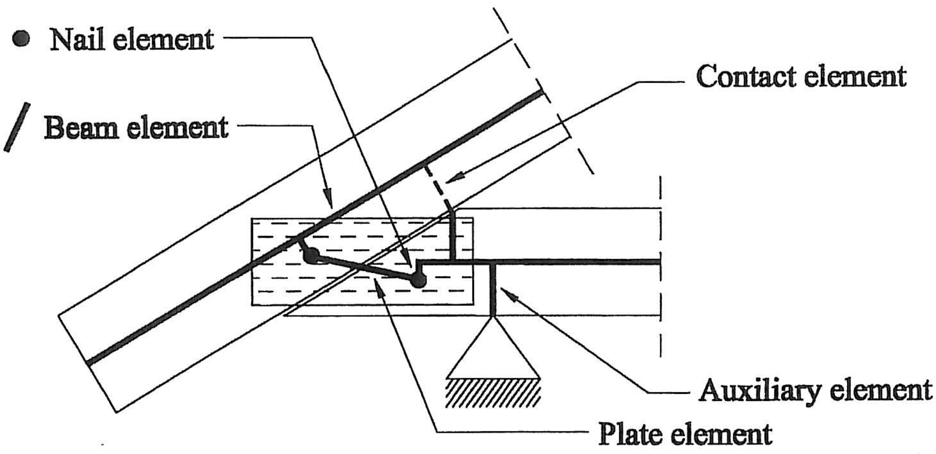
To show the general idea behind the model a heel joint is shown again but this time with the elements of the advanced model, see figure 2 .

The beam elements used to model the timber members are located at the system line of the timber. Furthermore, the beam elements are used as auxiliary elements that transmit the forces from a support, a nail group or from a contact element to the system line of the timber members.

The stiffness matrix for a beam element is given by the theory of Timoshenko beams. For the auxiliary elements the ingoing parameters (Young's modulus, E, shear modulus, G, cross sectional area, A and moment of inertia, I) should be estimated considering that these elements do not follow the system line.

A nail element is used to model the stiffness of a nail group and it connects a beam element with a plate element. Plate elements connect the nail groups with each other and contact elements are used to model contact forces between timber parts.

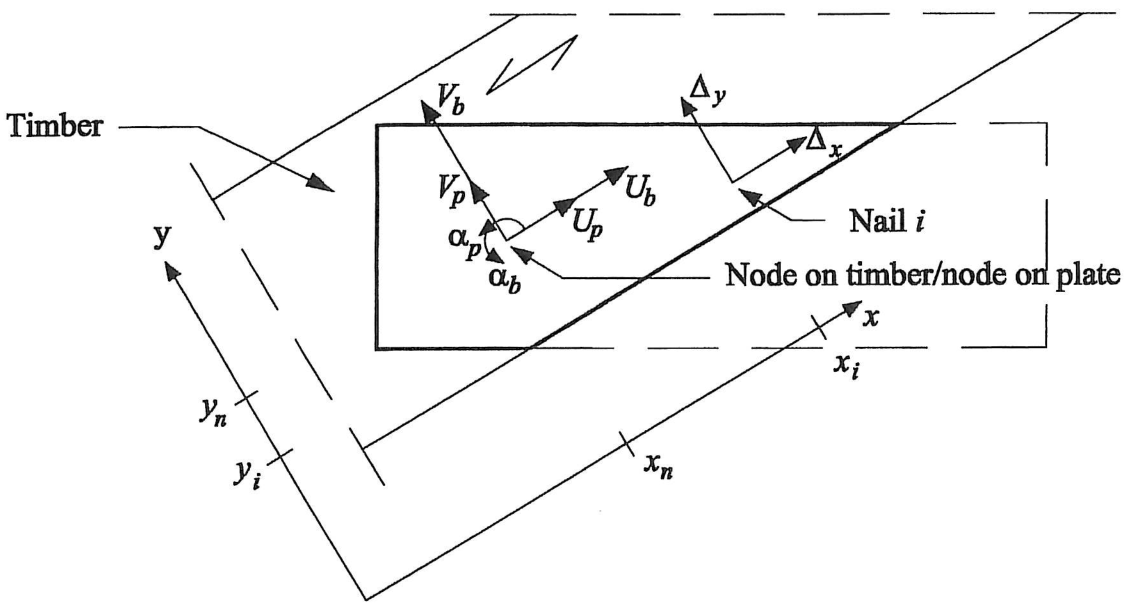
Figure 2: Advanced model of a heel joint.



2.1. Nail Element

The nail element connects one node on the timber to one node on the steel plate. It is chosen to place both nodes in the same point at the centre of gravity of the nail group - see figure 3 at the coordinates (x_n, y_n).

Figure 3: Nail element. The x-axis is parallel to the grain direction.



The displacements of the node on the timber are given by U_b, V_b and α_b and the displacements of the plate node are given by U_p, V_p and α_p. It is assumed that the plate and timber perform like stiff bodies in the joint region and that the rotations are small. The displacements Δ_x and Δ_y of nail i in the directions of the x, y-system are given by:

$$\Delta_x = \mathbf{q}_x^T \mathbf{u} \tag{1}$$
$$\Delta_y = \mathbf{q}_y^T \mathbf{u} \tag{2}$$

where:

$$\mathbf{q}_x = \begin{bmatrix} 1 & 0 & -(y_i - y_n) & -1 & 0 & (y_i - y_n) \end{bmatrix}^T \tag{3}$$
$$\mathbf{q}_y = \begin{bmatrix} 0 & 1 & (x_i - x_n) & 0 & -1 & -(x_i - x_n) \end{bmatrix}^T \tag{4}$$
$$\mathbf{u} = \begin{bmatrix} U_p & V_p & \alpha_p & U_b & V_b & \alpha_b \end{bmatrix}^T \tag{5}$$

The force on a nail, $p(\Delta)$, is estimated by the nonlinear expression:

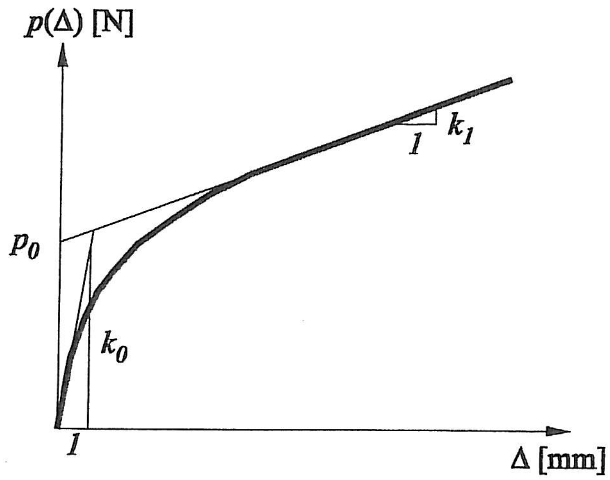
$$p(\Delta) = (p_0 + k_1\,\Delta)\left(1 - \exp\left(\frac{-k_0\,\Delta}{p_0}\right)\right) \tag{6}$$

where the absolute displacement, Δ, is found by:

$$\Delta = \sqrt{\Delta_x^2 + \Delta_y^2} \tag{7}$$

The stiffness parameters p_0, k_1 and k_0 in (6) are defined in figure 4 and they can depend on the angle between the grain direction and the principal axes of the plate.

Figure 4: Definition of the stiffness parameters used in the expression for the nail forces.



However, the only dependence found for the tested plate type (GNA 20 S from Gang-Nail Systems) is p_0 as a function of the angle v between the nail force vector and the grain, see Nielsen (1996):

$$p_0 = \frac{p_0(v=0^o)+p_0(v=90^o)}{2} + \frac{p_0(v=0^o)-p_0(v=90^o)}{2}\cos(2v) \qquad (8)$$

The stiffness parameters $p_0(v=0^o)$, $p_0(v=90^o)$, k_1 and k_0 are determined by tests by Nielsen (1996).

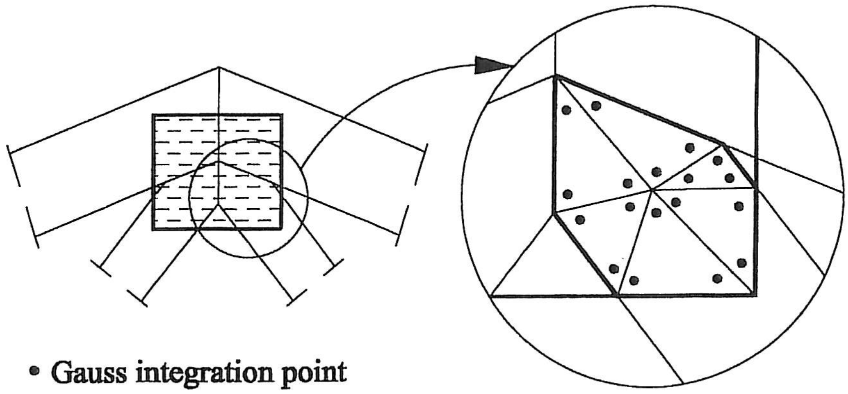
By setting up the internal and external work for a virtual displacement of a nail, see e.g. Foschi (1977) or Nielsen (1996), the local stiffness matrix $\mathbf{K}$ for the nail element is given by integration over the area A of the nail group:

$$\mathbf{K} = \int_A \Im \frac{p(\Delta)}{\Delta}\left(\mathbf{q}_x\mathbf{q}_x^T + \mathbf{q}_y\mathbf{q}_y^T\right) dA \qquad (9)$$

where $\Im$ is the nail density.

A nail group is bounded by 3,4,5,6,...,n edges. Integration is performed by splitting the nail group area into triangles and by using Gauss Integration over each triangle. An example of this is shown in figure 5 where the method is illustrated on a peak joint.

Figure 5: Illustration of splitting a nail group with a six-sided polygon into triangles. The integration points are shown with dots.



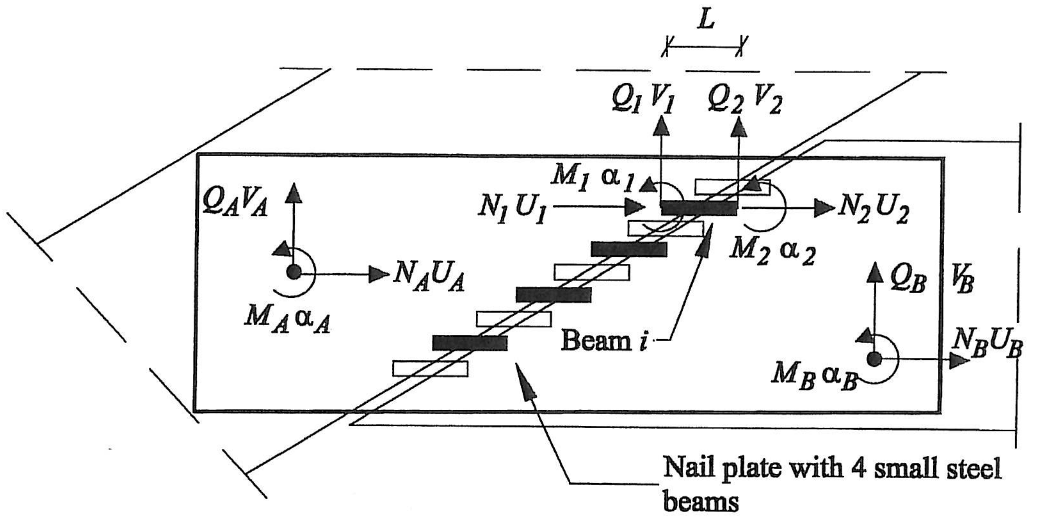
The integration can be done with 3 or 6 integration points in each triangle but tests have shown that 3 integration points in each triangle are sufficient.

2.2. Plate Element

A plate element connects the two nail elements. The plate is modelled by small Bernoulli beams between the two stiff plate regions, see figure 6.

The deformations $U_1, V_1, \alpha_1, U_2, V_2$ and α_2 of beam i are calculated from the displacements $U_A, V_A, \alpha_A, U_B, V_B$ and α_B of the two plate nodes A and B. The stiffness matrix for the plate element is set up by a summation of the stiffness matrices of the small beams, see Nielsen (1996). The forces N_A, Q_A, M_A, N_B, Q_B

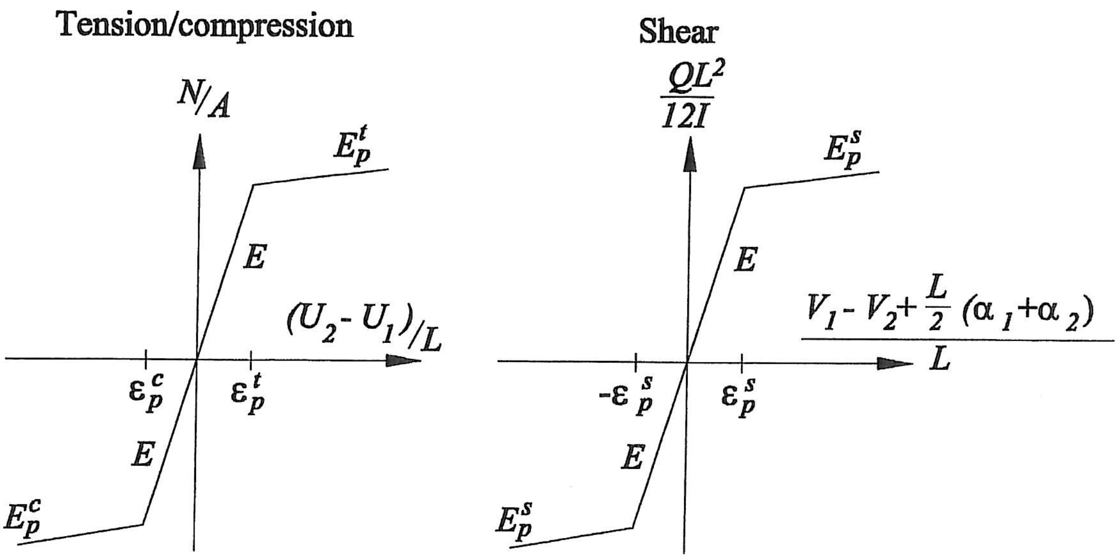
Figure 6: Plate element.



and M_B at the two plate nodes A and B are calculated similar by summation of the forces at the ends of the small beams.

The small beams are assumed to behave bi-linear elastic, see figure 7.

Figure 7: Bi-linear load-displacement curve for the small steel beams.



In compression the tangent stiffness E_p^t is used to model the stiffness of beams in buckling.

Values of ε_p^t, ε_p^c, ε_p^s, E, E_p^t, E_p^c and E_p^s for the nail plate are determined by tests by Nielsen (1996). Furthermore, the following parameters are needed as input for the model:

L :	Length of the beams
I :	Moment of inertia of one beam
A :	Cross sectional area of one beam

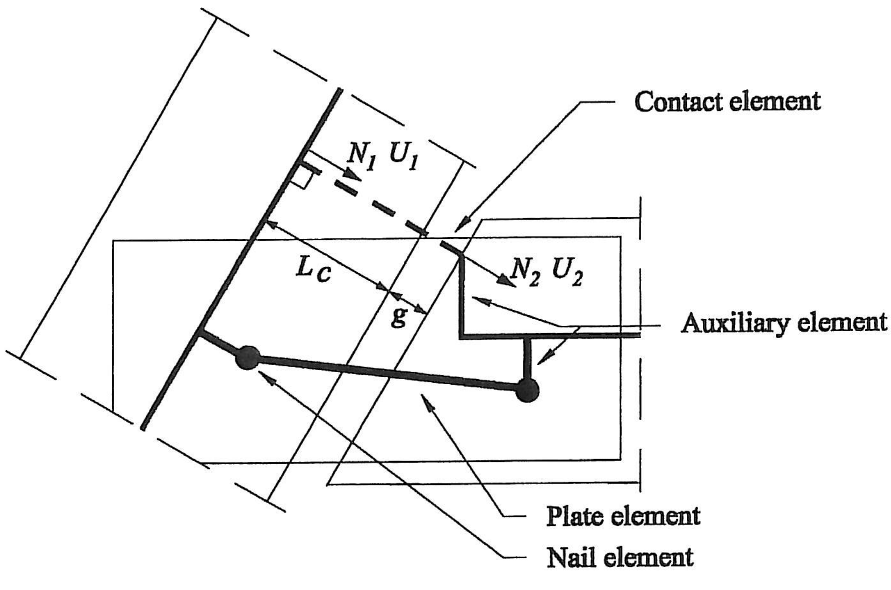
The parameters I and A are determined from the appearance of the beams on the line between the two stiff plate areas even though they may be difficult to determine when the joint line is not perpendicular to the main axis of the plate.

The value of L is important for the behaviour of the joint. L is a measure of the plastic zone of the plate.

2.3. Contact Element

The contact element, see figure 8, is used to model contact between timber members. The element is activated if the gab $(U_2 - U_1)$ between the timber members becomes less than $-g$.

Figure 8: Contact element.



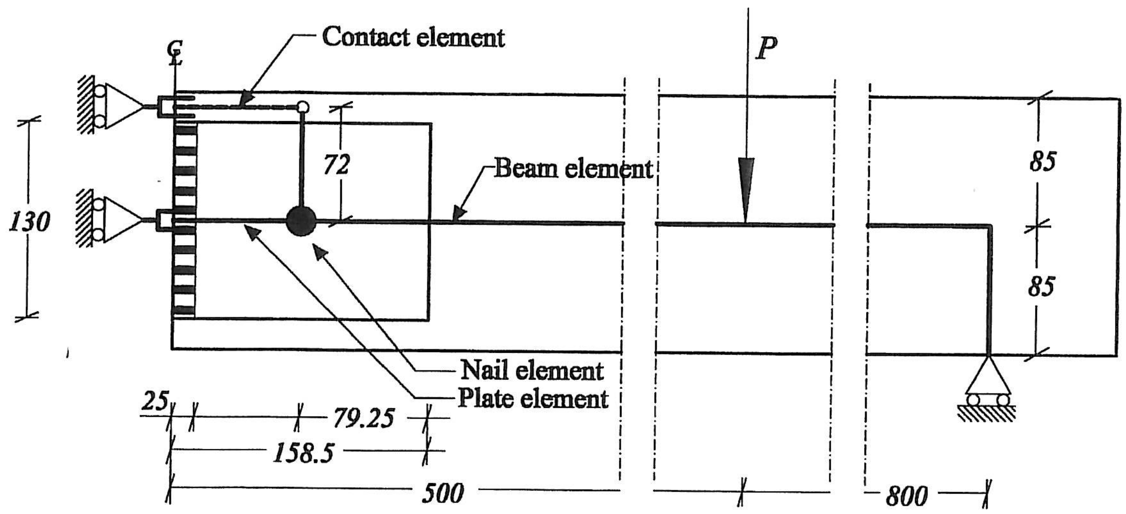
The stiffness matrix is identical to the stiffness matrix for the beam element but only normal forces is transferred. Friction between timber members can be implemented.

The input parameters are the length of the contact element L_c, the gab g, and Young's modulus E_c. The location and the cross sectional area of the contact element have to be estimated too. The stiffness of the joint is sensitive to the location of the contact element.

3. Comparison of TRUSSLAB with Tests

Tests on splices subjected to 4-point-bending have been performed to verify a model in TRUSSLAB. Figure 9 shows the model used in TRUSSLAB (symmetry is used).

Figure 9: TRUSSLAB model of splices subjected to 4-point-bending. Dimensions in mm.



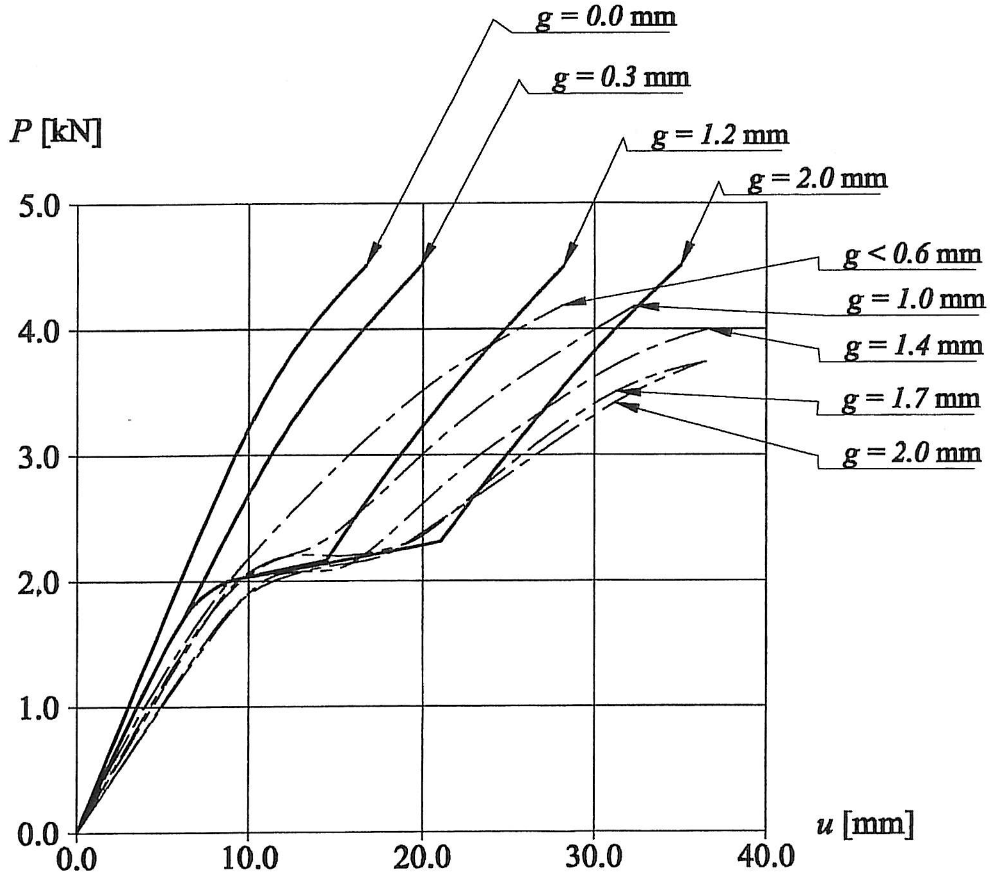
The timber used for the tests is Swedish spruce of strength class K-24 according to DS 413. The nail plates are GNA 20 S from Gang-Nail Systems and the thickness of the timber is 45 mm.

The load-displacement curves are shown in figure 10. The tests are performed with 5 different gab sizes (< 0.6 mm, 1.0 mm, 1.4 mm, 1.7 mm, 2.0 mm) and the models in TRUSSLAB are performed with 4 gab sizes (0.0 mm, 0.3 mm, 1.2 mm, 2.0 mm).

On the first part of the load displacement curves it is seen that TRUSSLAB overestimates the stiffness a bit. When contact occurs the overestimation of the stiffness is increased. This is caused by the butt effect (fibres are pressed into each other) in the contact zone and it is found that the load displacement curves from the tests and from TRUSSLAB become more identical when using a reduced value of Young's modulus for the contact element.

Several other tests with splices subjected to bending have been compared with results from finite element models in TRUSSLAB. These load displacement curves show corresponding results.

Figure 10: Load displacement curves for splices in 4-point-bending. Curves from tests are drawn with dash-dot lines.



4. Conclusion

The advanced analog is capable of estimating the load-displacement curves well for splices subjected to bending.

From tests with tensile splices it is seen that TRUSSLAB estimates these load-displacement curves very well, see Nielsen (1996).

The advanced analog has the advantages as mentioned in the introduction but many things still have to be solved.

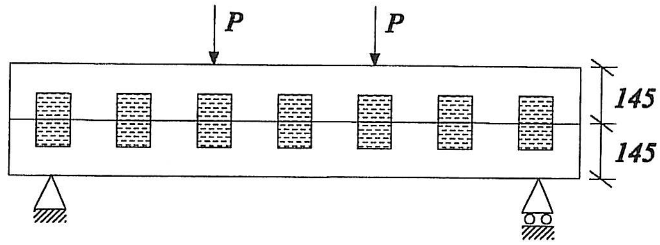
There must be some clear rules for estimating the parameters such as the length of the beams in the plate element, Young's modulus for the contact element and the placement of the contact element. Perhaps the length of the beams should be treated different so that the length of the beams depends on whether the beams are in tension, compression or shear or even in elastic or plastic state. Nielsen (1996) suggests to include different values of L in the compression/tension terms and in the shear terms in the stiffness matrix.

Investigations within these parameters will be a part of the future work. Failure conditions will also be implemented in the advanced model.

A lot of tests will be performed to verify the results of the model. E.g. tests with knee and heel joints, and full-scale tests with trusses will be performed.

At the time being 2 graduate students are studying and testing the advanced model on a compounded beam made up of two beams held together with nail plates, see figure 11.

Figure 11: Two beams held together with nail plates. Dimensions in mm.



The span of the compounded beam will be approximately 6 m and the height of each beam is 145 mm. Thickness is 45 mm.

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2. Nielsen, Jacob, 'Stiffness Analysis of Nail-Plate Joints Subjected to Short-term Loads', Ph.D.-Thesis, Dept. of Building and Technology and Structural Engineering, University of Aalborg, Denmark, 1996.

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PAPER NO. 2: J. Nielsen: *Stiffness Analysis of Nail-Plate Joints subjected to Short-Term Loads.* Ph.D.-Thesis. ISSN 1395-7953 R9613.

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